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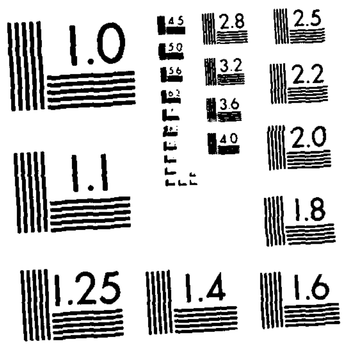
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NUMERICAL CALCULATIONS OF THE RESPONSE OF A SPINNING SPHEROIDAL PAYLOAD TO CONING MOTION

GENE R. COOPER

MARCH 1988

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

ABERDEEN PROVING GROUND, MARYLAND

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2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
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4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-MR-3661	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Ballistic Research Laboratory 6b. OFFICE SYMBOL (If applicable) SLCBR-LF	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, MD 21005-5066	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Army Ballistic Research Laboratory 8b. OFFICE SYMBOL (If applicable) SLCBR-DD-T	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, MD 21005-5066	10. SOURCE OF FUNDING NUMBERS

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62618A	1L1 62618AH80		

11. TITLE (Include Security Classification)

NUMERICAL CALCULATIONS OF THE RESPONSE OF A SPINNING SPHEROIDAL PAYLOAD TO CONING MOTION

12. PERSONAL AUTHOR(S)
Cooper, Gene R.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Memorandum Report	FROM ____ TO ____	1988 March	13

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
01	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Singular Integral, Numerical Calculations, Spheroidal Container, Rotating Liquid, Eigenvalue

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A method for numerically evaluating a particular type of singular integral coupled with a complex eigenvalue problem is presented here. This presentation provides the information needed to carry out the numerical calculations found in the cited Murphy report. This technique has proven useful for calculating the moment exerted by a low-viscosity spinning liquid in a coning spheroidal container.

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DD Form 1473, JUN 86 Previous editions are obsolete.

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I. INTRODUCTION

Murphy[1] has studied the moment exerted by a low-viscosity spinning liquid in a coning spheroidal container and presented some computations. The purpose of this report is to elaborate on some of the numerical methods used by Murphy. He indicates the need of further clarification of two numerical problems. The first problem involves the numerical evaluation of integrals that have a singularity in their integrands. The second problem deals with calculating complex zeroes (i.e.,complex eigenvalues) of a complex function.

II. NUMERICAL INTEGRATION

The calculations used in Reference 1 basically center around numerically evaluating integrals. These integrals are found in Equations (6.22)-(6.23), (8.6) and (8.9) of his report and are repeated here for convenience:

$$(U_{km}(s_{km}))_i + Re^{-1/2} a_{km} = 0 \tag{6.22}$$

where

$$(U_{km})_i = \frac{2if^\sigma}{D\rho_o^\sigma(1-\rho_o^2)^{|m|/2}}\left[mP_k^{|m|}(\rho_o) - \frac{(1-\rho_o^2)}{f(1-e\rho_o^2)^{1/2}}\frac{d}{d\rho}\left(P_k^{|m|}(\rho)\right)_{\rho_o}\right]$$

$$D = 4(1-b^2)$$

$$b = (m + is_{km})/2$$

$$\rho_o = bf(1 + b^2(f^2-1))^{-1/2}$$

$$e = 1 - f^{-2}$$

$$a_{km} = \frac{c_{kkm}}{b_{kkm}}$$

$$b_{kkm} = f\int_{-1}^{1}\left(P_k^{|m|}(\omega)\right)^2(1-e\omega^2)^{-1/2}d\omega$$

$$\begin{aligned} c_{kkm} &= \frac{i}{2}\int_{-1}^{1} \frac{mfP_k^{|m|}(\omega)}{(1-\omega^2)^{1/2}}\left(\frac{A_{km}}{\alpha_1} + \frac{B_{km}}{\beta_1}\right) \\ &+ (1-\omega^2)^{1/2}\left(\frac{A_{km}}{\alpha_1} - \frac{B_{km}}{\beta_1}\right)\frac{d}{d\omega}\left(\frac{P_k^{|m|}(\omega)}{(1-e\omega^2)^{1/2}}\right) d\omega \end{aligned} \tag{6.23}$$

$$(x/a)^2 = (f\rho/\rho_o)^2\omega^2$$

$$(r/a)^2 = \left[\frac{1-\rho^2}{1-\rho_o^2}\right](1-\omega^2)$$

---

[1] Murphy, C H.,"*Moment Exerted on a Coning Projectile by a Spinning Liquid in a Spheroidal Cavity*," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, Technical Report BRL-TR-2775, December 1986.

$$\tau C_{LM_p} = \frac{i}{5}(f^2-1)(9d_2-1) + \frac{i(f^2-1)}{4f\hat{K}} \int_{-1}^{1} Re^{-1/2} \left(\frac{A_0}{\alpha_1} + \frac{B_0}{\beta_1}\right) \left(\frac{1-\omega^2}{1-e\omega^2}\right)^{1/2} P_2^1(\omega) d\omega \tag{8.6}$$

$$\tau C_{LM_v} = \frac{3}{8Re^{1/2} f\hat{K}} \int_{-1}^{1} \left[\omega(\alpha_1 A_0 + \beta_1 B_0) + \frac{\alpha_1 A_0 - \beta_1 B_0}{f(1-e\omega^2)^{1/2}}\right] d\omega \tag{8.9}$$

Re	= Reynolds number
(k,m)	$= \{(4,0),\ (2,1),\ (4,1),\ (6,1)\}$
$\hat{K}$	= sine of the coning angle
σ	= 0 if k - $\mid m \mid$ is even
	= 1 if k -$\mid m \mid$ is odd
i	$= \sqrt{-1}$
$P_k^{\mid m \mid}$	= associated Legendre function
f	= fineness ratio = $\frac{height/2}{maximum\ radius}$
τ	= ratio of coning rate to spin rate [1]
s	$= (\varepsilon + i)\tau$
α_1	$= [-2i(b + C_{10})]^{1/2}$
β_1	$= [-2i(b - C_{10})]^{1/2}$
C_{10}	$= f^{-1}[1 - e\omega^2]^{-1/2}\omega$
A_{km}, B_{km},	
A_0, B_0	= functions of ω and s_{km} [1]
$(x/a), (r/a)$	$= \left(\frac{axial\ displacement}{maximum\ radius}\right), \left(\frac{radial\ displacement}{maximum\ radius}\right)$
$C_{LM_{p,v}}$	= non-dimensional side moment coefficients
d_2	$= \frac{(s-i)(1-f^2)}{3f(U_{21})_i}$

Equation (6.22) represents the normal velocity boundary condition that must be satisfied at the wall of the container for non-forced motion. $(U_{km})_i$ is the (k,m)th mode of the normal inviscid velocity for $k = 2,4,6$ and $m = 0,1$. The variable a_{km} is obtained by expanding the normal wall boundary layer correction in the least squares formulation given by the terms c_{kkm} and b_{kkm} . Expression (8.6) gives the non-dimensional side moment due to the inviscid pressure plus the boundary layer correction to this pressure resulting from the velocity boundary layer at the wall. The boundary layer also introduces a further correction to the liquid side moment found from the viscous diffusion terms. This correction is given by Equation (8.9). The definitions as well as the interpretation of the remaining variables in the above equations can be found in Murphy's report and the List of Symbols at the end of this report. The corresponding integrations are carried out over the range of $[-1,1]$. By inspection it is revealed that each integrand is an even function of ω . Hence each integration is equal to twice that integration over the interval $[0,1]$. For constant-amplitude motion, $\varepsilon_{km} = 0$, Murphy points out that the integrands in Equations (6.23) and (8.6) have a singularity at $\omega = \pm\omega_c$, where

$$\omega_c = f \mid m - \tau \mid [4 + f^2(m-\tau)^2 e]^{-1/2} \tag{2.1}$$
$$m = 0, 1$$

After some straightforward algebra it can be shown that each integral in Equations (6.23) and (8.6) can be written in the form:

$$I = i(-1)^{(1-|m|)} \int_0^{\omega_c} \frac{F(\omega, \alpha_1, \beta_1) d\omega}{\sqrt{\omega_c - \omega}} + \int_{\omega_c}^1 \frac{F(\omega, i^{(1-|m|)}\alpha_1, i^{|m|}\beta_1) d\omega}{\sqrt{\omega - \omega_c}} \tag{2.2}$$

where $F(\omega, \alpha_1, \beta_1)$ is an analytic function on $[0,1]$. Equation (2.2) shows explicitly the type of singularity found in the corresponding integrands. Identify the first integral in Equation (2.2) by I1 and second by I2. Using the substitution $t^2 = \omega_c - \omega$ in I1 and $t^2 = \omega - \omega_c$ in I2 allows the integral I to be written as:

$$I = 2i(-1)^{(1-|m|)} \int_0^{\sqrt{\omega_c}} G(t, \cdots) dt + 2 \int_0^{\sqrt{1-\omega_c}} G(t, \cdots) dt \tag{2.3}$$

The integrals shown in Equation (2.3) are no longer singular. These integrals along with the integral given in Equation (8.9) can now be integrated by standard numerical quadratures. The particular numerical quadrature that was used for Reference 1 is an iterative Simpson's rule with adaptive gridding. This is a variation of a technique given by Sampine and Allen[2] where the real integrand is replaced by a complex integrand.

III. ROOT FINDER

The results given in TABLE 3 of Reference 1 can now be found by using a numerical root-finding technique on Equation (6.22). For completeness TABLE 3 is reproduced on page 4.

The procedures described above allow the values of this analytic complex function to be calculated. The eigenvalues (Murphy's s_{km}) were readily found by applying a Muller[3] algorithm to Equation (6.22). Its main advantage is that it requires functional values only, not derivatives. Experience has shown that with reasonable initial guesses for s_{mk}, the Muller algorithm obtains the desired roots with only a few iterations.

IV. DISCUSSION

The procedures presented in this report show one method of eliminating the singular point in the required integrals. These integrals as well as the eigenvalues can then be evaluated using standard methods found in text books on numerical analysis. The numerical methods presented here were found to work successfully when applied to the Murphy [1] integration and the eigenvalue problems. All of the remaining calculated results found in

[2] *Sampine and Allen, 1973, Numerical Computing: An Introduction, W.B. Saunders Company.*

[3] Muller, H., 1956: A Method for Solving Algebraic Equations Using an Automatic Computer. Math. Comput. 10,208-215.

Table 1: Comparison of Eigenvalues with Greenspan/Kudlick (TABLE 3. of ref. 1)

		τ_{km}	$Re^{1/2}\varepsilon_{km}$		
(k,m)	f	Re=10^4	Re=10^4	Re=10^8	Greenspan Kudlick
4,0	1	1.3054	2.30	2.59	2.59
	2	.7964	2.81	3.09	3.33
	4	.4252	3.29	3.64	4.52
2,1	1	-.0026	1046.	1014.	1011
	2	.6037	-2.91	-2.82	–
	4	.8847	-1.31	-1.25	–
4,1*	1	-.7130	4.16	3.73	3.70
	2	-.2110	12.91	11.94	11.81
	4	.3828	-4.86	-4.64	-5.22

*Two other eigenvalues exist for this case. For f=1,the other τ_{41}'s are .3878 and 1.8203

Reference 1 can be obtained by a direct application of the formulas given there. Since this procedure is straight-forward, no further discussion will be presented here.

REFERENCES

1. Murphy, C.H., "Moment Exerted on a Coning Projectile by a Spinning Liquid in a Spheroidal Cavity," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, Technical Report BRL-TR-2775, December 1986.

2. Sampine and Allen, 1973, Numerical Computing: An Introduction, W.B. Saunders Company.

3. Muller, H., 1956: A Method for Solving Algebraic Equations Using an Automatic Computer. Math. Comput. 10, 208-215.

List of Symbols

a_{km}	coefficient in Eq. (6.22)
$A_{km} B_{km}$	functions of ω and s in Eq. (6.23)
b	$(m + is)/2$
b_{kkm}, c_{kkm}	denominator and numerator of a_{km}
C_{10}	factor in Eqs. (8.6) and (8.9)
$C_{LM_{p,v}}$	complex coefficient of the transverse liquid moment
d_2	coefficient in the expression (8.6)
e	$1 - f^{-2}$
F, G	integrands in integrals I,I1 and I2
f	fineness ratio
I,I1,I2	integrals in Eqs. (2.2)-(2.3)
$\hat{K}$	sine of the coning angle
k	axial wave number
m	azimuthal wave number
$P_k^{\|m\|}$	associated Legendre function of the first kind
Re	Reynolds number
s	$(\varepsilon + i)\tau$
s_{km}	eigenvalue of s
t	integration variable
$(U_{km})_i$	factor in Eq. (6.22)
α_1, β_1	functions of ω Eqs.(8.6),(8.9)
ε	non-dimensionalized damping
σ	0 if $k - \mid m \mid$ is even; 1 if $k - \mid m \mid$ is odd
τ	non-dimensionalized coning frequency
τ_{km}	eigenfrequency
ω_c	latitude at which $\alpha_1 = 0(\omega = \omega_c)$ or $\beta_1 = 0(\omega = -\omega_c)$
$()_i$	inviscid quantity

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